OPTIMIZATION OF THE SEXTUPOLE SCHEME AND COMPENSATION OF THE TIME-DEPENDENT FIELD ERRORS DURING SLOW EXTRACTION FROM THE SUPERCONDUCTING SYNCHROTRON SIS300

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Abstract

The SIS300 synchrotron, planned for the new Facility for Antiproton and Ion Research (FAIR) at GSI-Darmstadt, will become the first superconducting synchrotron worldwide using $\cos(\theta)$ magnets for resonant slow extraction. A multi-objective optimization algorithm has been developed to design the nonlinear magnet scheme of the SIS300 lattice. The optimization algorithm aims to determine the gradients of the chromatic and harmonic sextupoles for the highest extraction efficiency. To this end, it makes use of the analytical descriptions of the slow extraction separatrices, of the resonance driving modes and of the chromaticity. The optimization algorithm also accounts for the sextupole errors on the dipole magnets, and it is used to compensate the persistent current decay which occurs in $\cos(\theta)$ magnets during the slow extraction plateau. Tolerances on the magnet field errors have been established at the limits where the compensation is no longer valid.

OPTIMIZATION OF THE NONLINEAR MAGNET SCHEME

The nonlinear magnets included in the SIS300 synchrotron are the chromatic and harmonic sextupoles used for chromaticity correction and slow extraction, respectively. SIS300 will be hosted together with the SIS100 synchrotron in an underground tunnel. The shape of SIS100 determines the geometry of the tunnel, which fixes the dipole layout of SIS300. Thus, compromises concerning the positions and phase advances between the optical elements of SIS300 have to be accepted. However, unless a careful design of the nonlinear magnet scheme is realized, the excitation of unwanted resonances in the so-called *original lattice* leads to a coupling of the horizontal and vertical planes, a reduction of the dynamic aperture and an overall particle loss. Therefore, a tailored design or *optimized lattice* has been developed for the SIS300 synchrotron. The design is based on the use of several sextupole families, whose gradients, grouping, and number of independent families are determined by means of an optimization algorithm. The optimization aims to satisfy, simultaneously, the following goals:

- Orientation of the separatrices to match the entrance angle at the position of the electrostatic septum.
- Correction of the horizontal chromaticity to fulfill the Hardt condition, i.e. decouple of the entrance angle from the particle's momentum.
- Excitation of the third integer resonance, $3Q_x$, which generates the slow extraction.
- Minimization of the resonances Q_x, $Q_x + 2Q_y$, $Q_x - 2Q_y$ also excited by the sextupoles at first order.
- Minimization of the term α_{xy}, which couples the tune shift suffered by a particle and its corresponding emittance.

To fulfill each of these goals, an *optimization term* is built based on: (1) the analytical model for the slow extraction from Kobayashi [1], which describes the geometry of the separatrices, (2) the analytical expressions for the resonance driving modes from Bengtsson [2], which describe the excitation of the different resonances and the amplitude-dependent tune-shift, (3) the analytical expression of the chromaticity and of the Hardt condition.

In the SIS300 lattice the working point has been adjusted to achieve a task separation between the chromatic and the harmonic sextupoles, see details in [3]. For this reason, the optimization terms are grouped in two separated functionals, as a function of the chromatic or the harmonic sextupole gradients. Each optimization term has been multiplied by a factor, to weight it according to the needs; e.g to fully cancel the excitation of a given unwanted resonance for a working point placed very close to it. The

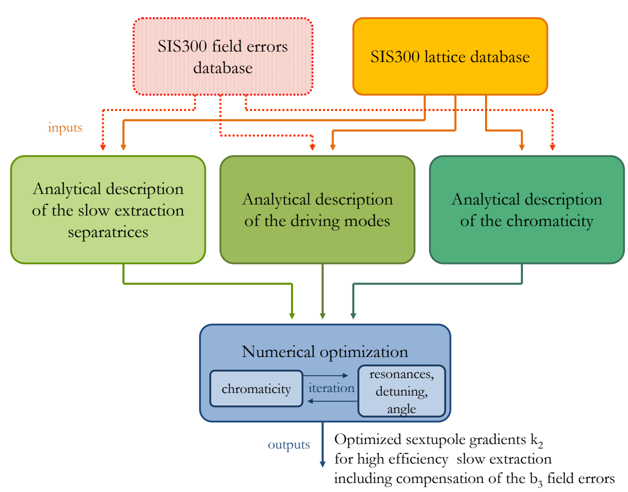

Figure 1: Scheme of the optimization procedure.

two functionals, described in [3], are minimized iteratively until convergence is found. A scheme of the optimization procedure is represented in Figure 1.

To evaluate the performance of the optimized lattice, beam dynamics simulations have been run with the code *Elegant* [4]. In order to simulate the RF-knockout extraction planned for SIS300, the beam has been excited in the horizontal phase-space with the use of *white noise*, a random signal with a flat power spectral density. The resulting short-term dynamic apertures (3000 turns) for the original and optimized lattices are compared in Figure 2. On one hand, both dynamic apertures have a similar size in the horizontal axis, where an unstable area within the physical aperture is needed for slow extraction. On the other hand, the dynamic aperture is more than one order of magnitude bigger in the vertical direction for the optimized lattice. As a result, the extraction of all particles is possible for the optimized lattice independent of their vertical amplitude, and the extraction efficiency reaches a value of 96.4%. In the original lattice the slow extraction is not possible since the beam is lost in the magnet apertures and in the electrostatic septum, as shown in Figure 3.

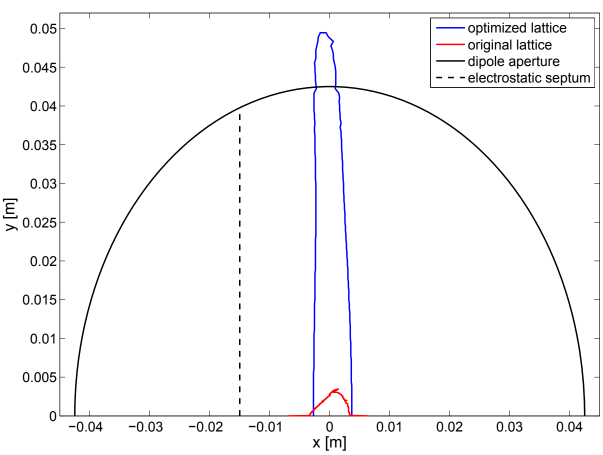

Figure 2: Short-term dynamic apertures of the original and optimized lattices, represented together with the apertures of the dipole magnets and electrostatic septum.

COMPENSATION OF THE FIELD ERRORS

The field quality in superconducting $\cos(\theta)$ magnets is determined by the positions of the superconducting cable and the static and time-dependent effects of the current in the cable. The sextupole field component in the dipoles, b_3, is the most harmful of the field errors for the slow extraction process. The effect of the sextupole field component in the dipoles can be included in the analytical models in which the optimization algorithm is based. Therefore, the sextupole field error in the dipole magnets can be compensated by means of optimized gradients for the different families of sextupole magnets.

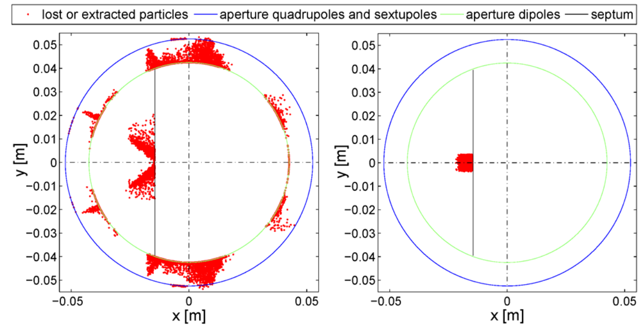

Figure 3: Left: Losses produced in the apertures of the magnets and on the electrostatic septum, for the original lattice. No beam can be extracted in this case. Right: No losses are produced in the magnet apertures of the optimized lattice. All the beam is extracted at the electrostatic septum, where an extraction efficiency of 96.4% is reached.

An example of the slow extraction in the presence of the predicted sextupole field error is plotted in Figure 4. In the left plot the field error is not compensated. As a result, the Hardt condition is no longer fulfilled and a big broadening of the separatrices, with a 10 times bigger spread on the entrance angle at the septum, is generated. The extraction efficiency is decreased down to 80%. In the right plot the field error has been compensated, and a slow extraction efficiency of 93.6%, similar to that of the lattice with ideal magnets, is recovered.

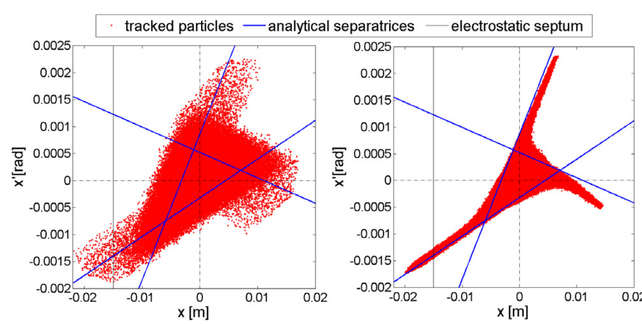

Figure 4: Phase-space plots of a multi-particle simulation for slow extraction. The left figure shows the widening of the separatrices caused by the b_3 field errors in the dipole magnets. The extraction efficiency in the presence of the predicted field error decreases down to 80%. The right figure shows the effect of the compensation by means of a new set of optimized gradients for all sextupole families. An extraction efficiency of 93.6%, similar to that of the lattice with ideal magnets is recovered.

With the use of this compensation method, the extraction efficiency has been calculated for the different combinations of systematic and random sextupole field components of the dipole series. This has been done for three different scenarios: (A) all dipoles have been measured *cold*, i.e. in superconducting conditions, prior to their installation in the tunnel. In this case the systematic and random components are known. (B) all dipoles have been mea-

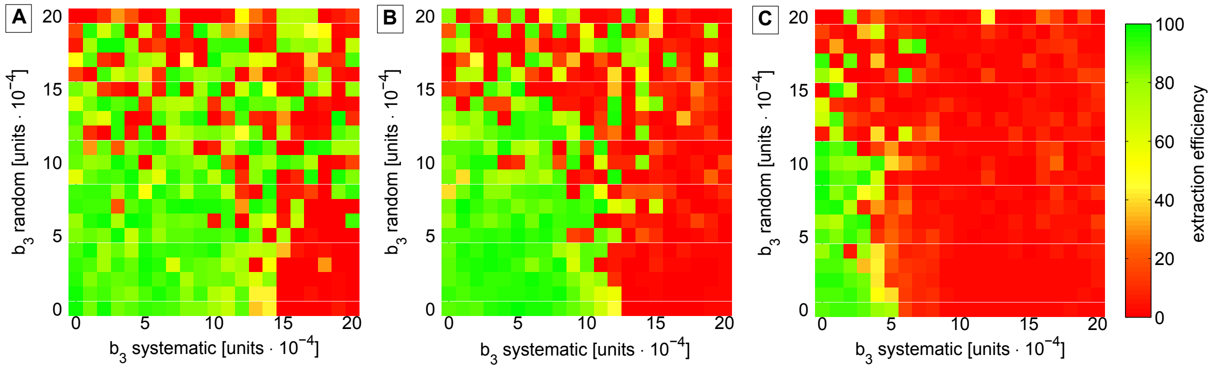

Figure 5: 2D histograms showing the extraction efficiency as a function of the systematic and random sextupole field components in the dipole magnets. A: the systematic and random components are known and have been compensated. B: only the systematic component is known and has been compensated. C: no component is known, and no compensation is applied. A different random seed has been used for each grid point

Table 1: Tolerances for the field components [units · 10^{-4}]. Unless specified, the systematic components are given.

components	b_3 systematic	b_3 random	b_5 b_7 b_9 b_{11} b_{13} b_{15}	a_2	a_3	a_4	a_5 a_6 a_7 a_8 a_9
tolerances	A / B / C: 11 / 10 / 3	A / B / C: 14 / 13 / 11	>10	≤1	4	2	>10

sured *warm*, i.e. at room temperature, only few have been measured *cold* and *warm-cold* correlations have been established. The mean value measured *cold* is assumed for all magnets. Thus, the systematic component is known. (C) no measurements have been realized on the magnets. Therefore, the field errors are not known. Only the known components can be compensated with the use of the optimization algorithm. For this reason the magnet tolerances for the scenarios A and B are much more relaxed than those for case C, as shown in table 1.

In $\cos(\theta)$ magnets the field components vary as a function of time during the slow extraction. This time dependence is caused by the decay of the persistent current at constant current plateaus. To compensate the time dependence of the sextupole component, $b_3(t)$, the optimization algorithm can be used to calculate the optimal sextupole gradients at each instant, $k_2 = k_2(t)$. Thus, ramped sextupole magnets during the slow extraction plateaus are proposed as a compensation method for the characteristic persistent current decay of the $\cos(\theta)$ magnets [3].

Those field errors different from the sextupole field error cannot be compensated with the use of the optimization algorithm. Thus, tolerances for these errors have been proposed based on the efficiency results of the slow extraction tracking simulations. As shown in table 1, relaxed limits have been found except for the skew quadrupole, a_2, which couples the horizontal and vertical axes and is particularly harmful for the performance of the slow extraction and has to be controlled down to 1 unit.

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CONCLUSIONS

A tailored design for the nonlinear magnet scheme of the SIS300 superconducting synchrotron has been developed to ensure a high efficiency slow extraction. The optimal gradients of the different sextupole families are the result of a multi-objective optimization algorithm developed in this work. As a result, in the optimized lattice, the dynamic aperture has been vertically maximized such that all particles can be extracted independent of their vertical amplitudes. An extraction efficiency over 95% has been achieved.

With the use of this optimization algorithm a compensation scheme for the static and time-dependent sextupole field errors has been developed by means of optimized sextupole gradients and ramps. Tolerances on the field components have been determined when the compensation is no longer valid. These tolerances will be used as an input for the magnet designers.

REFERENCES

[1] Y. Kobayashi. *Theory of the resonant beam ejection from synchrotrons.* Nuclear Instruments and Methods, 1970.

[2] J. Bengtsson. *The Sextupole Scheme for the Swiss Light Source: An Analytical Approach.* Technical Report SLS 9/97, Swiss Light Source, March, 1997.

[3] A. Saa Hernandez. *Design and Optimization of the Lattice of the Superconducting Synchrotron SIS300 for Slow Extraction.* PhD thesis, IAP Frankfurt, 2011.

[4] M. Borland. *Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation.* Technical Report LS-287, Advanced Photon Source, September 2000.